MICROWAVES

They are radio waves that range in length from about a quarter of an inch to two feet. Investigated during the war for their utility in radar, they are now widely applied in communication

by J. R. Pierce

WITHIN a generation radio waves have changed our lives and linked the human race together. We have filled the air with them, in many wavelengths. There are the long radio waves in the broadcast band which travel a little beyond the horizon in the day and go thousands of miles at night. There are shorter radio waves that bounce around the earth, linking the continents by telephone and telegraph. Still shorter waves that reach only to the horizon carry FM and television signals. The still shorter microwaves, rifled in sharp beams, relay TV from hilltop tower to hilltop tower across the country. And still shorter radio waves—but the still shorter radio waves are not called radio at all: they are known as heat and light. One warms you before the radiator, and by means of the other the contents of this page reach your eyes in what might be called short-range radio facsimile transmission.

Radio waves are easy enough to describe in these terms, but what, precisely, are they? That is not so simple. We can begin to understand them by considering the familiar waves on water, which illustrate the basic principles of wave motion.

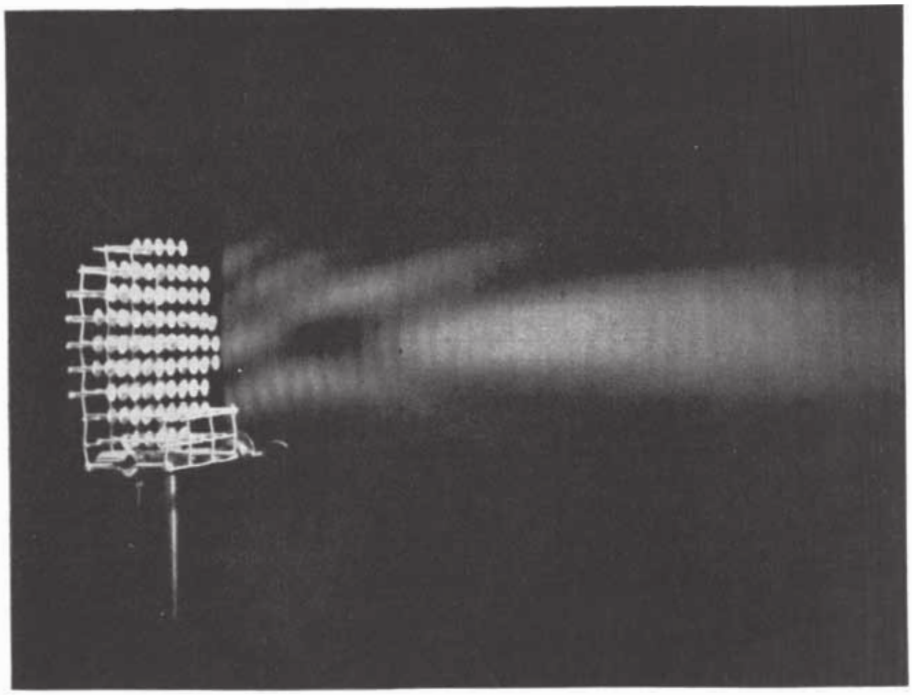
One of the first things that occurs to us is to measure the waves in some way, to attach numbers to them. We can measure their wavelength—the distance between crests. They also have a velocity, and we can estimate this by noting how fast their crests move along past a boat bobbing up and down on them. We can measure their frequency by counting the number of wave crests that pass the boat per minute or second. The frequency can also be calculated from the other two numbers: it is the velocity divided by the wavelength.

Just what happens in a wave that makes it the peculiar thing that it is? Let us imagine ourselves moving along with a wave above its crest, as we might in a helicopter. The water in the wave, which has been lifted above the level of the ocean and set in motion, has two forms of energy. It has potential energy: like that of a car at the top of a hill, or of water behind a dam. Its motion also gives it kinetic energy: like the energy of a rapidly coasting car, or of a spinning flywheel. As the crest moves forward, water ahead of it is scooped up and set in motion, and the water behind it simultaneously falls and loses its forward motion, much as does gravel sliding down from the back of a moving dump truck. Thus the two kinds of energy flow with the wave, being continually transmitted to the water ahead of it and continually lost by the water left behind it.

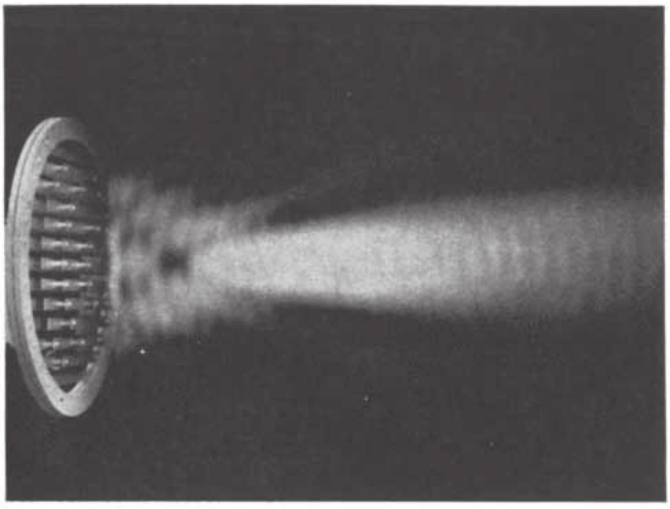
Like water waves the impalpable waves of radio have wavelength, velocity and frequency and involve a continual flow of two forms of energy. But they also have more complex properties, and for our understanding of them we are indebted to the great British physicist James Clerk Maxwell.

Maxwell's Equations

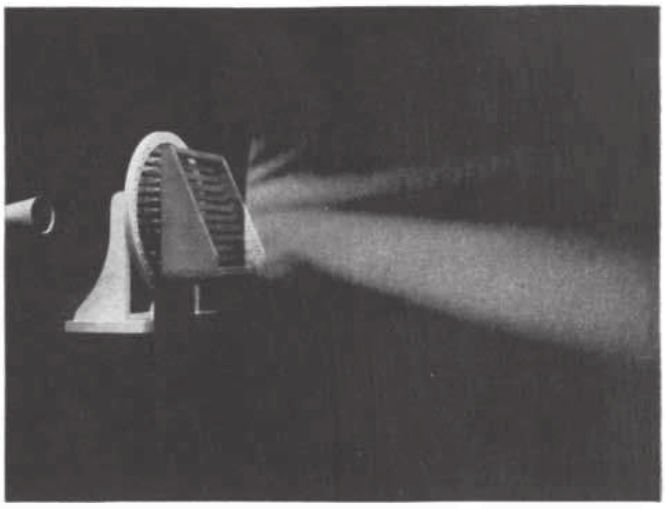
Maxwell came to lay the foundation for radio through studying the laws of electricity and magnetism. He recognized that electric and magnetic fields were forms of storage of energy in space. Electric and magnetic fields had been known before, but the correct equations



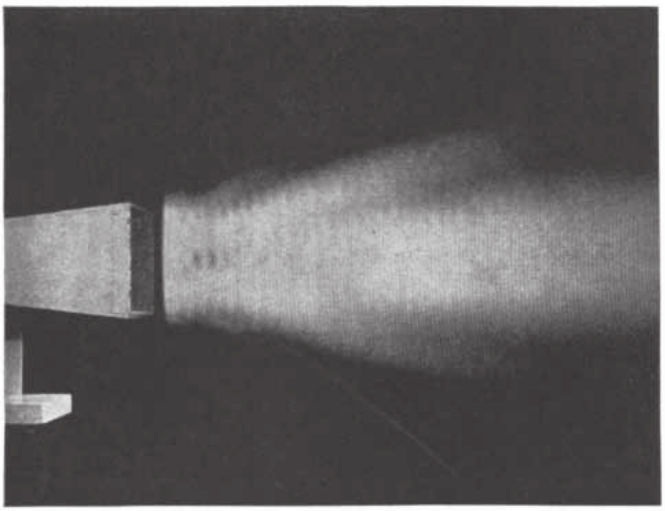
SOUND WAVES of the same length as microwaves are focused by an array of disks. Microwaves would behave in the same way. The waves are made visible by a scanning technique developed by W. E. Kock and F. K. Harvey of Bell Telephone Laboratories. In this technique a microphone and a small electric light are swung back and forth across the beam in such a way that the strength of the sound signal is indicated by the brightness of the light. The swinging light is then photographed by a time exposure.



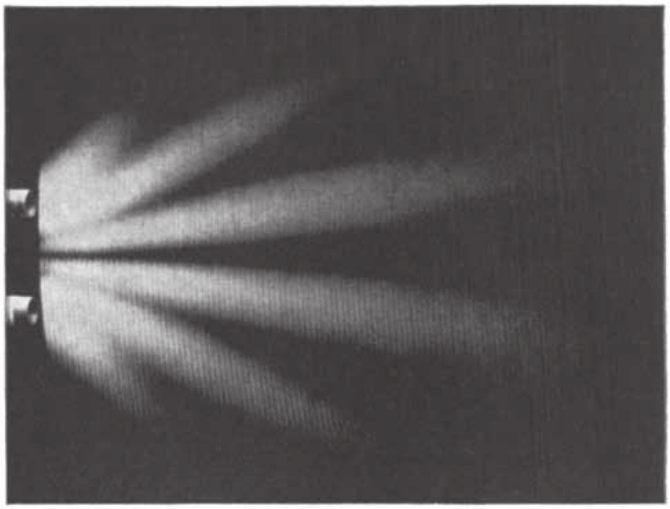
LENS composed of metal strips focuses sound waves in much the same way as the disks on the preceding page. These photographs were also made by Kock and Harvey.



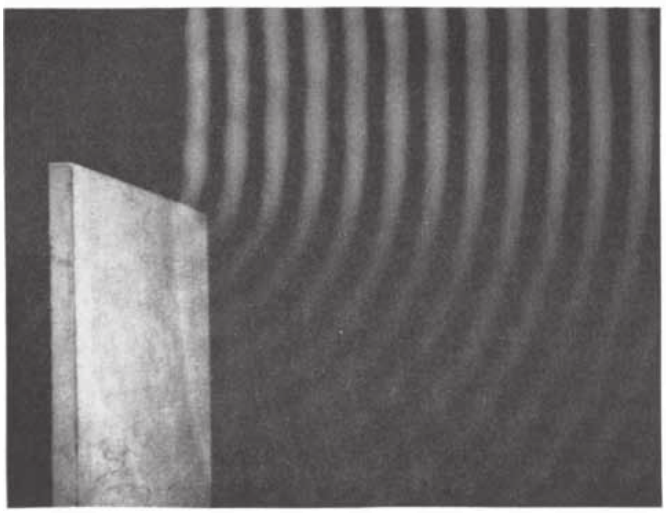
PRISM composed of metal strips is placed in front of the strip lens, tilting the focused sound beam downward. At the far left is the horn that emits the sound waves.



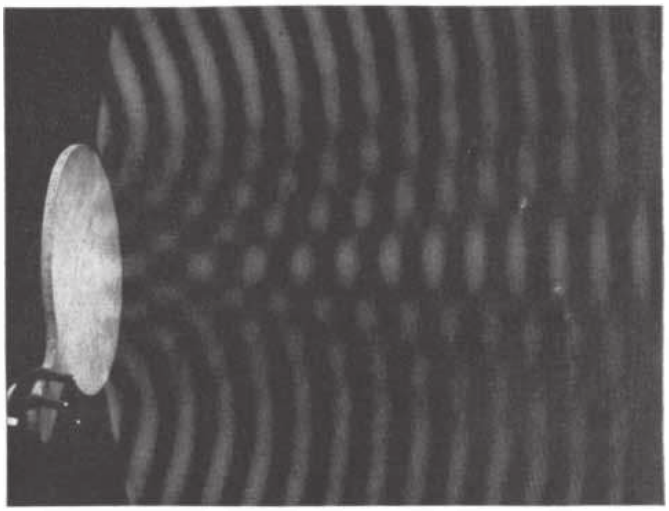
SQUARE HORN emits sound waves in this pattern. Most of the energy is concentrated in the long central lobe, but some of it is in the lobes at top and bottom.



TWO ROUND HORNS emit sound waves that are out of phase. The result is that the waves along a line between and parallel to the horns are canceled out.



STRAIGHT EDGE diffracts a row of perpendicular sound waves so that their lower ends are curved. The source of the sound waves is to the left of the plate.



ROUND PLATE diffracts sound waves so that they interfere with one another. The reinforcement and cancellation of the waves creates the pattern in the center.

governing their behavior had not. These equations Maxwell deduced, and he published them in his great book on electricity and magnetism in 1873.

I once saw a play, *Wings Over Europe,* in which the scientist hero died rapturously muttering Maxwell's equations. As a tool in the hands of physicists and engineers Maxwell's equations have far more practical meaning than Einstein's on general relativity, and yet, while the latter have often appeared in print in popular articles, Maxwell's equations have been rather slighted. These pregnant equations are reproduced at the right. They describe the relations between electric and magnetic fields: the laws that each obeys, and the way in which a change in one produces the other. Their two brief lines sum up a tremendous range of natural phenomena.

Electric and magnetic fields cannot be seen or touched or tasted, and it is hard to describe them in words except by analogy. A magnetic field may be regarded as analogous to the kinetic energy of a swiftly moving automobile, and an electric field as analogous to the potential energy of a heavy body raised to a height. Just as the swiftly moving car can coast up a hill, losing kinetic energy and gaining potential energy, so a magnetic field can decay and produce an electric field. Just as a car coasting down a hill loses potential energy and gains velocity and kinetic energy, so a decaying electric field can produce a magnetic field. Maxwell's equations are the law of such changes.

His equations deal with waves composed of electric and magnetic fields—electromagnetic waves. Studying his equations, Maxwell found that they predicted that such waves should travel through any medium which did not conduct electricity. And he found that their speed through air or a vacuum should be the same as the speed of light! Was light perhaps the electromagnetic waves his equations described?

Physicists of that day were skeptical: they regarded his conjectures on the nature of light as more ingenious than true. Experimental demonstration was needed. But to test his theory by experiments with light was an impracticable enterprise, for the wavelength of light is so short (about 20 millionths of an inch) and the frequency of oscillation so high (600 million million times a second) that it seemed hopeless to produce such waves by means of electric circuits, or to measure their electric and magnetic fields with electric instruments.

Maxwell's fruitful equations suggested, however, another possibility. They implied that rapidly changing currents should produce electromagnetic waves. Why not try to produce waves of longer wavelengths than light and see how they behaved? In 1888 the German physicist Heinrich Hertz per-

$$\oint E_s \, ds = -\iint \mu \frac{\delta H_n}{\delta t} \, dA$$

$$\oint H_s \, ds = \iint \left(J_n + \epsilon \frac{\delta E_n}{\delta t} \right) dA$$

μ = permeability of vacuum

ϵ = dielectric constant of vacuum

ds = element of length

dA = element of area

E_s = electric field along any closed path

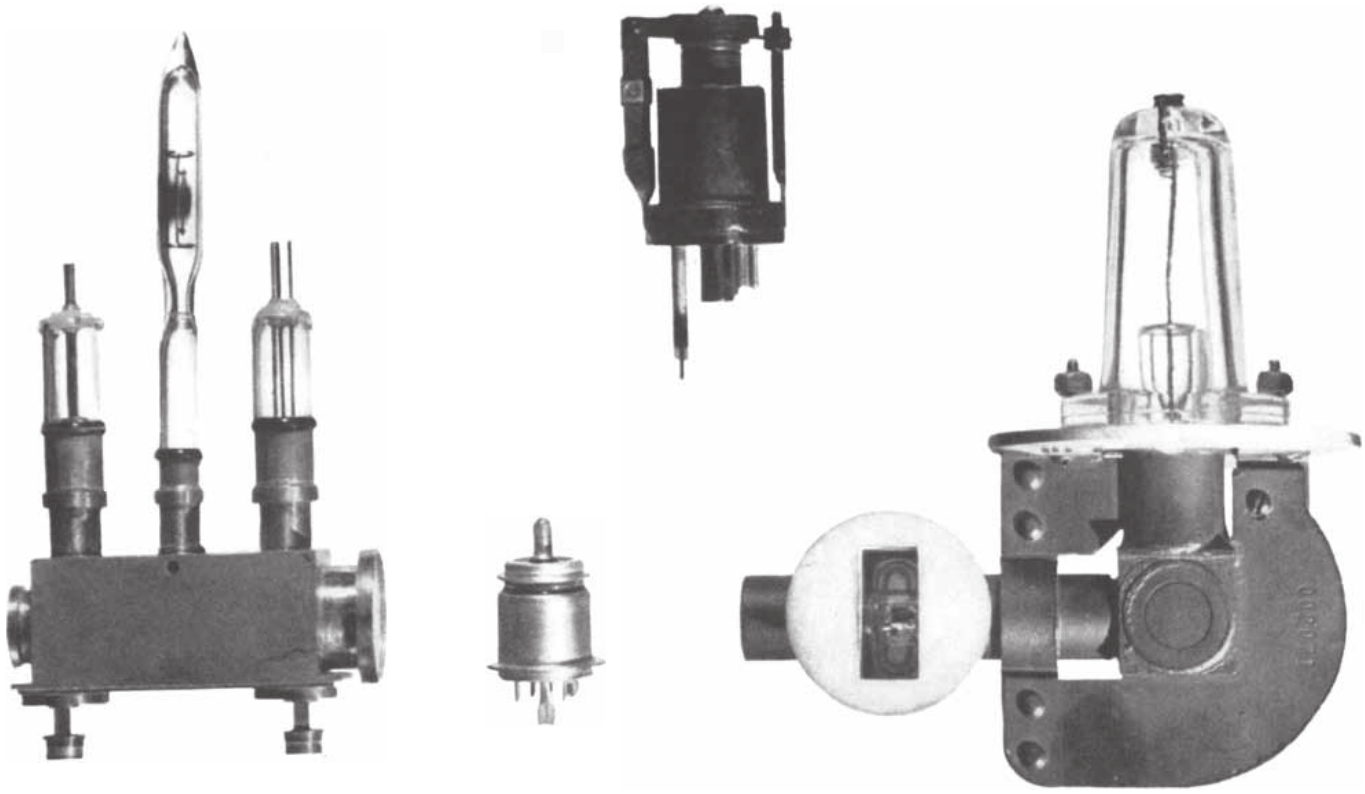
$\frac{\delta H_n}{\delta t}$ = rate of change in strength of magnetic field

H_s = magnetic flux along any closed path

J_n = density of convection current perpendicular to a surface bounded by the path

$\frac{\delta E_n}{\delta t}$ = rate of change in strength of electric field

MAXWELL'S EQUATIONS, which describe the behavior of microwaves and all other forms of electromagnetic radiation, are at the top of this illustration. The terms of the equations are defined in the list below.



FOUR MICROWAVE TUBES are shown in this photograph. At the left is a 6.25-millimeter traveling wave tube. The small tube at lower left center is a 7.5-centimeter microwave triode. At top center is a klystron that will generate waves from 7.6 to 8.8 centimeters in length. At the right is a 3-centimeter magnetron.

formed that historic experiment. He set up a very simple apparatus: To two metal plates, one charged very positive and the other very negative, were connected two rods with their ends close together, leaving a spark gap between them. When the voltage across the gap reached a certain level, the gap sparked and a sudden current flowed across. The current oscillated back and forth across the gap, and the oscillating current produced the first deliberately made electromagnetic waves. The waves traveled across the room, and Hertz detected them with an almost closed ring of wire, in which the waves induced a current that made tiny sparks jump across the gap between the ends of the ring.

Hertz went on to show that his waves could be reflected by a metal plate, just as light waves are reflected from a mirror; that they could be bent by a prism of pitch, just as light is refracted by a prism of glass; that they traveled with the same velocity as light.

Hertz's waves were the first microwaves. Their frequency was 500 million cycles per second (500 megacycles), and their length was about two feet. (Modern microwaves range in length from around a quarter of an inch to two feet.)

There is something of a paradox in the fact that the first man-made radio waves were microwaves, and today, more than 60 years later, microwaves are considered the newest thing in radio. The physicists and engineers who developed from Hertz's discovery the beginnings of radio quickly went from microwaves to longer wavelengths. There were good reasons for this: microwaves could not be transmitted farther than the short distance to the horizon, and it was very much harder to generate large powers at microwave wavelengths than at long wavelengths.

The vacuum tube, invented just before the First World War, made it possible to go to shorter and shorter wavelengths—as short as 1.5 meters (a little under five feet), which is used in television. And physicists retained their interest in microwaves, developing special types of tubes and equipment, including the magnetron and klystron, to handle them.

How, mainly under the stimulus of World War II, the microwave art rapidly expanded when the need arose is by now a well-known story (see "Radio Waves and Matter," by Harry M. Davis; SCIENTIFIC AMERICAN, September, 1948). The war supplied a tremendously important application of microwaves in radar and the equipment for generating high-power microwave signals. Microwaves suddenly changed from a laboratory tool to a major industry.

A Common Size

In trying to understand microwaves it is of primary importance to keep in mind their size. The behavior of waves is governed by their size in relation to the dimensions of things with which they interact. Let us go back to the example of the ocean waves. Suppose that one wants to build a breakwater, parallel to the shore, to protect the shore from waves coming straight in from the ocean. How long must he make it? Experience shows that this depends on the length of the waves. If we were thinking in terms of light or of radio waves, we would say that waves which strike the shore illuminate it. The purpose of the breakwater is to cast a "shadow"—a region of calm water where waves do not strike. It is a fundamental property of waves that objects cast distinct shadows only when they are large compared with a wavelength.

Of course the distance between the breakwater and the shore is important too. If a breakwater a mile long were put miles and miles out from the shore, it would not cast a distinct shadow. The waves would in effect bend around the ends and meet again some distance behind it. Where the crests of waves from the opposite ends arrived at the same time and reinforced each other, the waves would be high; where they met out of phase, the disturbance would be small. There would be a complicated pattern of disturbance behind the breakwater; its technical name is "diffraction pattern."

Light waves are so small that almost any object we think of is large in comparison. Thus in the case of light most

objects cast very distinct shadows. The waves of broadcast radio are about a quarter of a mile long. They will flow around a small hill and cast little or no shadow behind it. Because the transmitting antennas that send them out are small compared with a wavelength, such waves are broadcast from the transmitter in all directions; it takes an antenna many wavelengths in size to focus waves in a beam.

Much of the fascination of microwaves arises from the fact that they are in the range of sizes of most common objects. This makes them easier to handle and study than long radio waves or the minute light waves. For instance, with a little wire as the transmitting antenna one can broadcast microwaves in all directions; with a "dish" only 10 feet in diameter one can send them out in a narrow beam. For detecting microwaves we can use a crystal rectifier, which is just a little piece of silicon with a fine wire touching the surface. A crystal rectifier or crystal diode changes microwaves to direct current, which can be observed by means of a sensitive meter or galvanometer. Equipped with a crystal diode, a short wire antenna sticking out from it and a sensitive meter to read the current produced by the diode, one can explore a region in which microwaves travel and see where they are strong and where they are weak. Many microwave measurements are made in essentially this way.

To measure the length of waves that whiz by at 186,000 miles a second may seem no easy task, but there is actually a simple way, which Hertz used when he produced the first microwaves. When waves are reflected straight back from a flat surface, the incoming and reflected waves combine to form what are called standing waves. A quarter of a wavelength from the surface the crest of a reflected wave meets the crest of the next wave. At this point the combined crests give a strong signal. Half a wavelength from the surface the crest of a reflected wave coincides with the trough of the next wave, and the signal at this position is weak or zero. Thus strong and weak signals alternate at quarter-wavelength intervals from the surface. By determining with a detector where these distances are, one can easily measure the wavelength.

Standing-wave measurements are the backbone of microwave experimentation. They are used to determine not only wavelength but how much of the wave has been reflected. The reflected wave can cancel the incoming wave completely at any point only if all of the wave is reflected. If the wave is only partly reflected, the signal will nowhere be zero. One important use of standing-wave measurements is in designing devices which are meant to absorb microwaves instead of reflecting them.

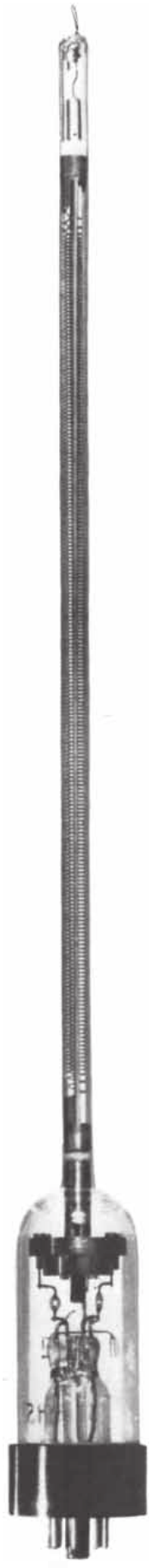
Like light, microwaves can be focused by means of concave mirrors. The larger the diameter of the mirror compared with the wavelength, the narrower is the beam. The 600-inch radio telescope of the Naval Research Laboratory can focus three-centimeter microwaves into a sharp beam less than a tenth of a degree wide. A concave mirror can also be used as a receiving antenna.

To act as a directional antenna a mirror must be shaped just right, so that the waves sent out from various parts of its surface travel along with their crests together and add up. There are other ways of making directional antennas. One is to use a horn like a megaphone. Microwaves sent into the small end spread out and leave almost uniformly over the large end. If the large end of the horn is many wavelengths in diameter, it can give a very narrow beam.

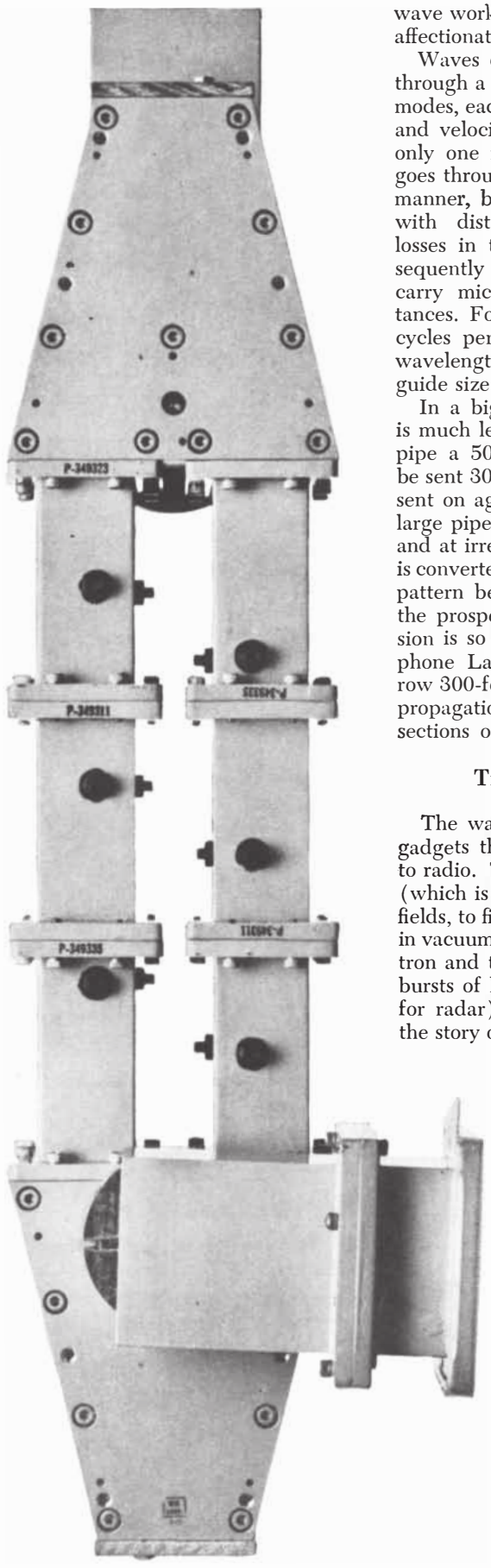
Horn antennas of the short, squat type need a lens at the mouth to correct for the difference in distance traveled by various parts of the wave. Such a lens could be made of glass. However, while glass is an admirable material for optical goods, 10-foot microwave lenses made of glass would be unduly heavy and expensive. What can one use as a substitute? It has been found that an array of regularly spaced little metal disks, close together in comparison with the length of a microwave, fills the bill nicely (*see photograph on page 43*). The disks are electrically excited by microwaves, just as the molecules of glass in a lens are by waves of light. Some microwave communication systems use lenses made of such arrays of disks, or sometimes of strips of metal.

Waveguides

In any radio system the waves not only are broadcast and received through the air but must also be guided within the transmitting and receiving equipment. In ordinary radio this is done by wires, much as wires transport a telephone message or electric power. Now a pair of wires will guide microwaves, but in a very unsatisfactory manner. The currents fluctuate much more rapidly than do those in a power line or a telephone line—perhaps 10,000 million times a second, as opposed to 60 times a second for power or a few thousand times a second in telephony. The very rapidly fluctuating currents tend to radiate microwaves from bends and irregularities into space. The waves just leak off the wires. Hence in microwave radio wires are replaced by metal pipes called waveguides, which carry the waves very satisfactorily when the diameter of the pipe is about the same size as the wavelength. Among micro-



TRAVELING-WAVE TUBE that generates 7.5-centimeter microwaves accelerates electrons in long coil.



WAVEGUIDES carry microwaves in relay equipment. This assembly separates microwave channels in a receiver and adds them in a transmitter.

wave workers waveguides have become affectionately known as "plumbing."

Waves of a given frequency can go through a pipe in many patterns, called modes, each with a different wavelength and velocity. When the pipe is small, only one mode can travel. The wave goes through the pipe in a well-ordered manner, but it dissipates fairly rapidly with distance because of electrical losses in the walls of the pipe. Consequently small waveguides are used to carry microwaves only for short distances. For a frequency of 50,000 megacycles per second, corresponding to a wavelength of 1/4 inch, an appropriate guide size is 3/16 inch by 3/32 inch.

In a bigger pipe, the loss of energy is much less. Potentially, in a two-inch pipe a 50,000-megacycle signal might be sent 30 miles and then amplified and sent on again. The trouble is that in a large pipe many modes travel together, and at irregularities or bends one mode is converted into others, so that the wave pattern becomes chaotic. Nevertheless, the prospect of long-distance transmission is so attractive that the Bell Telephone Laboratories have built a narrow 300-foot-long building to study the propagation of microwaves through long sections of waveguide.

Traveling-Wave Tube

The waveguide is only one of many gadgets that microwaves have brought to radio. There are the cavity resonator (which is used to produce high electric fields, to filter signals, to provide circuits in vacuum tubes, and so on), the magnetron and the klystron (used to produce bursts of high power, notably as pulses for radar), and a host of others. But the story of most of them has frequently been told, and this is not the place for a detailed catalogue of microwave equipment.

There is, however, a relatively new type of microwave tube which merits particular notice. This is the traveling-wave tube. It is of special interest because it promises to be of increasing importance in the field of microwaves and because it well exemplifies the wave nature of microwaves.

Like the klystron, the traveling-wave tube makes use of a long beam of swiftly traveling electrons. In the klystron a microwave resonator is used to build up strong electric fields, which accelerate and bunch the electrons as they pass quickly through a hole in the resonator. In the traveling-wave tube, on the other hand, the electric fields are not very strong. Instead, an electromagnetic wave is guided along beside the electron stream in such a way that the wave travels at almost the same speed as the electrons. Thus an electron continues to be acted on by the wave crest as it moves along, and the effect builds up.

Several different means can be used to slow the wave down so that it will travel with the same speed as the electrons. The most common practice is to use a coil of wire or a helix, much like a stretched screen door-spring. For a tube to amplify 7.5 centimeter waves, the coil might be a tenth of an inch in diameter and 10 inches long. The wave will travel along the wire of the coil with almost the speed of light. If there are 130 inches of wire in the 10-inch coil, the wave will travel down the coil with about 1/13 the speed of light, and this is just about the speed of electrons accelerated by a voltage of 1,600 volts.

The signal to be amplified is fed from a waveguide onto the coil or helix at the end near the source of electrons. The electrons and the wave travel along together and the wave acts on the electrons of the beam to bunch them. The electron-bunches in turn act to strengthen the wave in the circuit. After a little distance of travel, the wave increases in strength so that, in a typical case, its power doubles in less than an inch of travel. We can visualize the waves as waves on water, and we can think of the electron stream as a breeze that blows gently past the waves and raises them higher and higher as they travel.

Traveling-wave tubes give much more gain than other microwave tubes. One traveling-wave tube can amplify the power of a signal by 10,000 times, while a microwave triode gives an amplification of only 10 times, and klystrons give something intermediate. Moreover, traveling-wave tubes can amplify shorter microwaves than other devices can. Tubes made at the Bell Telephone Laboratories have amplified waves of 50,000 megacycles. Besides this, traveling-wave tubes will amplify bands of frequencies thousands of megacycles wide, in contrast to the narrow range amplified by klystrons or triodes. This is important because the amount of information a signal can carry is proportional to the width of the band of frequencies comprising it. To carry the human voice in telephony requires a band of frequencies 4,000 cycles wide, and one television signal takes about a thousand times that band width, or four million cycles.

It is easy to see that one of the great benefits of microwaves is the huge addition that it will make to our channels of communication. The section of the

microwave-range between 6 centimeters and 7.5 centimeters, for instance, covers a band width of 1,000 megacycles—a band 1,000 times as broad as that covered by all of the conventional AM broadcast stations together.

By making it possible to amplify broad bands of frequencies in one tube, the traveling-wave tube may permit the sending of several television signals through one piece of equipment, so that separate equipment will not be needed for each television channel as at present. This intriguing possibility is for the future. In their present commercial use, as in a microwave radio relay system built for the British Post Office by Standard Telephones and Cables, Ltd., they merely replace triodes or klystrons and do a somewhat better job.

In some communication systems information is sent by means of short pulses. As each pulse conveys a certain amount of information, the more pulses that can be sent in a second, the more information. It is therefore desirable to make the pulses as short as possible, and this requires a large band width. With traveling-wave tubes in the transmitter and receiver, microwave pulses lasting only a few billionths of a second have been sent and received over a path 22 miles long between branches of the Bell Telephone Laboratories at Holmdel and Murray Hill, N. J. These pulses are less than a tenth as long as the shortest pulses used in wartime radar. They travel through space as microwave signals less than 10 feet long. In addition to their possible uses in communication, such short pulses may improve the resolving power of radar. A radar can see targets separately only if they are separated by a distance comparable to the length of the radar pulse as it travels through space. Pulses as short as 10 feet might distinguish individual planes in a formation.

Noise

In any form of radio one of the most important matters to be considered is noise. When you listen to a weak broadcasting station, there is a frying or hissing noise in the background which is particularly noticeable in the absence of speech or music. When you watch television you may see a snowlike fluctuation even where the picture is supposed to be smooth black or gray. Similar disturbances are characteristic of all electrical communication. They are due to randomly fluctuating electric signals, either in nature or unavoidably produced by the transmitting and receiving equipment itself. Noise is what determines how powerful a signal we must have. In electrical communication the signal reaching the receiver must be enough larger than the noise to give the desired quality of communication. In radar one may detect a signal equal to or even smaller than noise. In television, telephony and radio the signal should be many times as powerful as the noise.

Now the power of the received signal can be increased by stepping up the power of the transmitter, by concentrating the power into a narrower beam with a larger transmitting antenna or by using a larger receiving antenna to intercept more microwave energy. Year after year microwave receivers are improved, so that they add less and less noise to the signal. So far as we know there is no physical limit to the possible improvement in this respect, and it is not idle to talk about receivers which would add essentially no noise to the received signal. We would still not be rid of noise, however. There would be noise from the earth, for warm bodies radiate microwaves just as they radiate waves of heat and light. If we pointed our noiseless receiver at the night sky, away from the Milky Way, we would receive perhaps less than 1/30 as much noise power, for the temperature of space dotted with ordinary stars is probably less than 10 degrees above absolute zero. If we pointed the receiver at the hot sun, we would get perhaps 30 times the signal the warm earth gave us, as the temperature of the sun is ordinarily around 10,000 degrees absolute. And from other points in the sky we might receive strong signals from so-called radio stars, often invisible, which radiate microwaves.

Thermal radiation sets an ultimate limit to the sensitivity of receivers in detecting weak signals. The province of the temperature or apparent temperature of natural bodies belongs to physics and astronomy, but the limitation imposed by thermal noise dominates all microwave applications. For this reason, the noisiness of present receivers is measured in terms of thermal noise.

A very good microwave receiver may have a noise figure of five, meaning that it generates a noise five times that which would be received from a body at the arbitrarily chosen temperature of 68 degrees Fahrenheit. Most of the receivers in use generate noise amounting to about 30 times on this scale. How much electric power does this noise represent? That depends on the width of the band of frequencies to which the receiver responds. For a band width of five megacycles, such as might be used in radar, the noise amounts to less than a millionth of a millionth of a watt. Let us assume that a radar can detect a signal which is just as strong as the noise, and that it sends out a signal of one million watts. It can detect a target if the echoed signal it receives has a millionth of a millionth of a millionth of the power sent out. And it needs to do this to see a tiny object over a hundred miles away!

I have not spoken of one form of noise with which we are familiar, the static of ordinary radio. In microwave radio there is no static! The fact that microwaves were not utilized for so many years after Hertz's discovery is an indication that man found it very hard to generate microwaves. Nature apparently finds it equally difficult, at least here on earth. Thunderstorms produce no microwave static. Neither do man-made devices, such as automobile ignition, X-ray machines or the like. One of the greatest advantages of microwaves is the freedom from natural and man-made interference.

Strange Reflections

The microwave art is not completely free from natural disturbances, however. Occasionally on a coast-to-coast television program, which is relayed *via* microwave towers in 106 hops across the country, you may see the picture dissolve briefly into a shower of speckles. This may be caused by any of several kinds of natural interruption in one or more of the 106 links. At the shorter wavelengths used in radar, intense rainfall can cause serious scattering of the waves, much as fog scatters light. In microwave communication, which generally operates at wavelengths longer than five centimeters, rain causes only slight interference. But there is another effect which may be much more serious: ground reflections.

When a microwave beam spans rough country, especially wooded areas, the part of the signal that strikes the ground is scattered and lost, and only that part which passes directly through the air reaches the receiver. Over water, however, or over the salt flats of Utah, microwaves that strike the water or ground are almost completely reflected. The reflected and direct waves reach the receiver by different paths, and whether they add to or cancel each other depends on the heights of the transmitting and receiving towers. Under such conditions relatively short towers may be better than tall ones, or it may be best to use a short tower at one end of the path and a tall tower at the other.

On the moon, where there is no atmosphere, reflections would cause no serious trouble. One would merely choose tower heights to make the direct and reflected waves add. On the earth variations in the atmosphere, particularly the decrease in density with height and the presence of water vapor near the ground, make the waves behave erratically. Since waves in the higher air travel faster than those near the ground, the path of the microwaves tends to bend toward the earth. At sea on calm nights microwaves sometimes hug the earth for hundreds of miles, instead of soaring into space beyond the horizon, because they are bent toward the sea,

TALL TOWERS support the transmitting and receiving antennas of the American Telephone and Telegraph Company microwave relay system. At the left is a steel tower near La Salle, Mich. Second from the left is a

reflected, bent toward the sea, reflected again, and so on. Even much less-pronounced effects will so alter the relative lengths of paths of direct and reflected waves as to cause them to cancel when, under other circumstances, they would add. Stratification of the air on very calm nights can make microwaves travel over two or more paths even without reflection from the ground. It is the bending of paths, from these various causes, that produces most of the fading encountered in microwave reception.

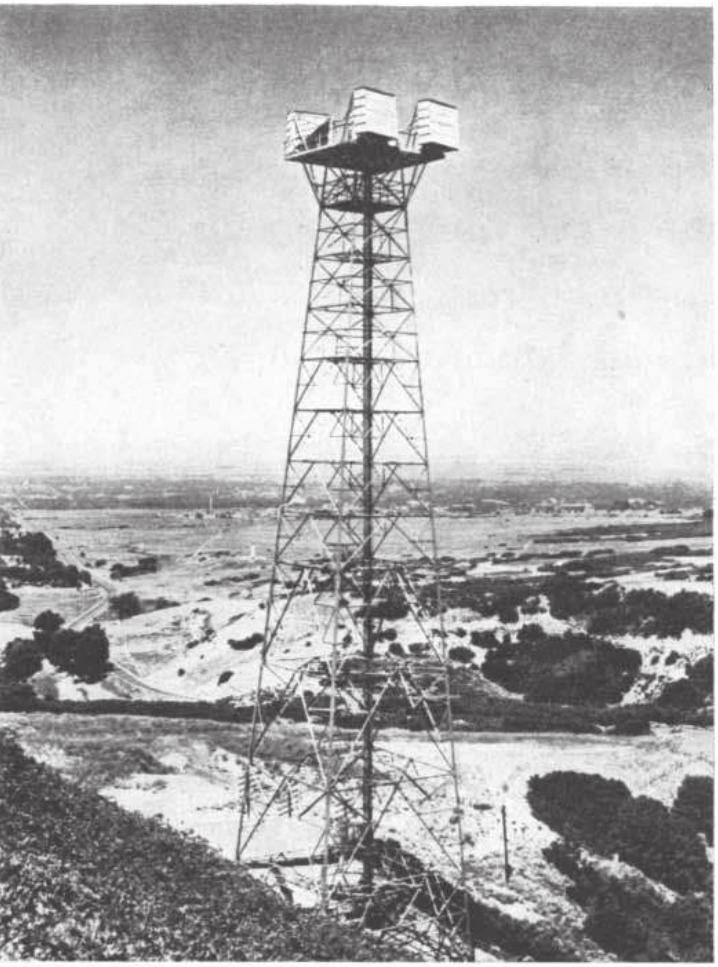
All of these phenomena, as yet imperfectly evaluated, affect the design of microwave communication systems. Year on year more data are gathered, and slowly our knowledge increases. With respect to propagation, microwave communication is and will for a long time be in a stage of doing and learning. Fortunately microwaves have a fundamental advantage over some of the waves we must work with today, such as the short-wave radio used in transatlantic telephony. Short-wave radio gets across the Atlantic by virtue of the fact that it is reflected around the earth by the ionosphere. But the reflection is erratic and sometimes fails altogether. Microwaves can be controlled better for the distances over which they are transmitted, and their range can be lengthened by relays. Even present microwave links give very reliable service indeed when they are compared with transatlantic telephony.

Microwaves at Work

The uses of microwaves by now make up a large catalogue. Astronomers study microwaves that come to us from the sun, the stars and clouds of gas in space for new "light" on those distant bodies. Physicists employ microwaves, as they use light, X-rays and beams of electrons, in deducing and measuring the properties of molecules, atoms and nuclei which are small far beyond the range of sight. Nuclear physicists harness microwaves to accelerate electrons and ions for bombarding nuclei and to study nuclear reactions.

In technology radar is still the most extensive application of microwaves. Because radar is largely military, much radar work is classified, and this makes it difficult to talk about it. In general, however, one can say that the microwave part of radar has not changed greatly since the war. Magnetrons with somewhat higher powers have been used. More tunable tubes have been produced. Microwave lenses have come into use as antennas, along with concave reflectors or mirrors. What has changed mainly is the complexity and use of radar systems. Present-day radars supply information to far more complex computers for use in pointing guns, and they not only can locate enemy planes but also are capable of directing guided missiles to them.

The chief civilian application of microwaves lies in the field of communications. As far back as 1931 the International Telephone and Telegraph Company, in collaboration with the Laboratories of Telephonic Material of France, used microwaves to bridge the channel from Calais to Dover. Their experimental microwave link operated on a wavelength of 18 centimeters and used a power of a few tenths of a watt. It supplied a single telephone circuit. On the verge of World War II preliminary steps toward microwave communication were being taken in this country. The wartime effort on radar interrupted this work. But the British, who frequently get there first in new fields of technology, made considerable use during the war of a microwave system known as Wireless Set No. 10.



concrete tower between Chicago and Milwaukee. Third from the left is a tower overlooking Salt Lake City. At the right is a double tower with its receiving antennas at one level and its transmitting antennas at another.

Before the end of the war two multichannel microwave communication systems had been built in this country, one by the Radio Corporation of America and the other by the Bell Telephone Laboratories. The latter still provides telephone service to Catalina Island. Early postwar days saw development of several microwave links for single-hop television transmission from pick-up to studio and from studio to transmitter. Similar inexpensive microwave systems find a variety of uses, including voice communication around airports. The use of single-hop systems was followed by development of various radio relay systems for voice communication along long pipelines, power lines and other purposes.

The most elaborate postwar application of microwave radio relay has been the Bell System's coast-to-coast microwave radio relay system for telephone and television, which was put into operation in 1951. The antennas carrying its 106 links across the country are located in all sorts of places, ranging from squat buildings on mountain peaks to tall concrete or steel towers on level plains. The antennas consist of horns with artificial dielectric lenses 10 feet square. The microwave frequency is around 4,000 megacycles per second. The transmitting tube is a triode with about half a watt power output. Such a long common-carrier system must meet much stricter requirements than a shorter, privately owned system. The system has a stand-by channel and elaborate alarm and control circuits to assure continuous service on all the relays.

The Future

What is the future of microwave communication? It has obvious advantages over stringing wire, particularly over water or rugged terrain. Some argue that it is and will be cheaper to install and maintain microwave systems than wire systems anywhere. If this proves to be so, microwave systems will be built up to the point where we run out of air channels. Indeed, this saturation will perhaps eventually be reached in any event. We may then add to the channels by putting microwaves in waveguide pipelines.

Microwave communication has much to recommend it in primitive areas or in areas where war or unrest is common. The French call a microwave link a Hertzian cable, and it is one cable that cannot be cut. As long as the transmitters and receivers can be defended, communication can be maintained.

If men ever go to the moon or to the planets, microwaves will provide easy communication back to earth. An earth-moon or even an earth-Mars microwave link could be set up with present microwave equipment—provided we can get to the far end to make the installation! Perhaps somewhat nearer is the possibility of a satellite vehicle circling the earth above the atmosphere. Such a vehicle could be used as a microwave relay point for round-the-world television and other communications.

Whatever the future developments, they will fit into the unalterable pattern of Maxwell's equations and the properties of waves slowly elucidated by the research of the past century. They will be new aspects of a science we already know. If they prove startling in their newness, they will be even more startling in their oldness, for they can be no more than as yet unseen parts of a pattern, a science, founded on the work of Maxwell and Hertz.

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